THE STUDY OF EFFECTS OF SPEED OF POWER SYSTEM PROTECTIVE UNITS WITH SPECIAL REFERENCE TO POWER SYSTEM STABILITY

by

Devendra S. Rajparia

B.Tech., Indian Institute of Technology,Bombay; India.

1962

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1964

Approved by:

M. C. Cottom
Major Professor

CONTENTS

INTRODUCTION

The stability of power system and protective relaying are closely allied in the proper operation of a system. The stability problem is that of investigating all effects that can or may cause parallel connected machines to pull out-of-step, i.e., to lose their synchronisms. Chronologically, the first major stability problem was that of small oscillations in alternator shaft speed due to the pulsating torques developed by steam engines as prime movers. In a modern system a high-speed steam turbine has no pulsating torque. The stability problem thus had become one of sudden changes in electrical load on the alternator. The multiple interconnection of wildly separated generating stations aggravates this problem. If any machine on the system loses speed due to an overload sufficient to cause a shift in the frequency and/or the terminal emf. , the machine will tend to draw excessive currents and to cause permanent damage to the machine. Thus it is of paramount interest to build the system protective devices to prevent damage, either due to frequency changes, voltage changes, speed changes or any contribution of these. In order to intelligently discuss the protective devices required, we require first a knowledge of power system stability in terms of what causes instability and what steps have been taken or can be taken to improve or obviate the problem.

THE SWING EQUATION AND ITS DERIVATION

Derivation of Swing Equation :-

Stability of a power system depends entirely on the performance of each of its individual components and the amount of power transmitted. The amount of power transmitted between a synchronous generator and motor, in a two machine system, through a resistanceless line has been shown[13] to be

$$P = \frac{E_G \times E_M}{X} \sin \delta \tag{1}$$

where,

P = Power transmitted from generator to motor

E_G = Generator terminal voltage

E_M = Motor terminal voltage

δ = Displacement angle between two rotors in electrical radians

X = Total inductive reactance; i.e., the sum of machine reactances and line reactances

The equation shows that the maximum power that can be transmitted is equal to

$$P_m = \frac{E_G \times E_M}{X} \quad \text{at } \delta = 90^\circ \tag{2}$$

It also indicates that for a given fixed system, any change in load can be adjusted only by the change in δ by retardation or acceleration of the rotors at the particular moments of change in load. Hence if the load requirement is such that it exceeds the value of P_m then δ will increase beyond 90°. If the system is not capable of meeting this requirement further retardation will result which ultimately puts the system out of synchronism. So the study of behavior of synchronous machines in the system is an essential part in the analysis of the system for transient stability.

The synchronous machines are rotating bodies and thus follow the rules of

mechanics. The torque on a machine is given by,

$$I \alpha = T_a \tag{3}$$

where,

I = Moment of Inertia

α = angular acceleration $= \frac{d^2\theta}{dt^2}$

θ = angular position, T_a = accelerating torque = $T_i - T_u$

T_i = shaft torque, corrected for torque due to torational losses

T_u = electromagnectic torque

If we take

$$\theta = \delta - w_1 t \tag{4}$$

with w_1 = rated normal synchronous speed, then

$$\frac{d^2\theta}{dt^2} = \frac{d^2\delta}{dt^2} \tag{5}$$

Substitution of equation (5) in (2) yields

$$I \frac{d^2\delta}{dt^2} = T_i - T_u \tag{6}$$

Multiplying equation (6) by the angular speed w, gives

$$M \frac{d^2\delta}{dt^2} = P_i - P_u = P_a \tag{7}$$

where,

M = Iw is the angular momentum

$P_i = T_i w$ is the shaft power input, corrected for rotational losses

$P_u = T_u w$ is electrical power output, corrected for electrical losses

P_a = accelerating power

Equation (7) is referred to as the swing equation of the system. In the steady state the input power is equal to the output power, thus the angle δ is constant. But when a disturbance is applied to the system, the accelerating power assumes some positive or negative value causing the angle δ to change.

Computation of Swing Curve :-

Substitution of equations (1) and (2) in equation (7) yields,

$$M \frac{d^2\delta}{dt^2} = P_i - P_m \sin\delta \tag{8}$$

The presence of Sin δ makes the swing equation non-linear in nature. Also the input power and the angular momentum, M, are not strictly constant. Formal solution of eq. (8) even for the simplest case of $P_i = 0$ and with damping neglected is not possible as it involves elliptic integrals. The solution becomes more difficult for the multimachine system, so some easy approximate method of solution has to be sought.

The methods available for the computation of the swing curve, which gives the variation of δ as a function of the time t, are;

(a) Point-by-point Solution Method

This is the most feasible method and is widely used for the solution of the swing equation. In this, one or more of the variables are assumed either to be constant or to vary according to assumed laws throughtout a short interval Δt, so that as a result of the assumptions made the swing equation can be solved for the changes in other variables during the same time interval. Then, from the values of the other variables at the end of the interval, new values can be calculated for the variables which were assumed constant. These new values are then used in the next time interval. Details of this can be found in reference 13.

(b) Graphical Integration[13]

(c) Selection of curves from sets of Pre-calculated Swing Curves [13]

(d) Phase-Plane Analysis of the Swing Equation[16]

When the non-linear differential equation of second order does not contain the independent variable t explicitly, much information concerning the properties of the solution is predictable by the phase-plane analysis. This method gives both critical clearing angle and time with only one numerical

integration.

The computation of swing curve for the given system is important from the point of view of design of the protective system for stable operation. The type of disturbance which is most important in stability studies is fault applied and subsequently cleared. The criterion for the determination of stability of a given system for a given load by itself gives only the information on clearing angle and not on the clearing time. But it is the clearing time which is of primary importance in the design of protective systems because the circuit breakers and protective relays have definite operating times which are independent of the angular displacement of the machines. Therefore, it is necessary to find the clearing angle when clearing time is given or vice-versa, to suit the existing protective system for stable operation or for new protective systems to be designed for stable operation.

TRANSIENT STABILITY ANALYSIS

Transient stability is an ever present problem which needs continuous studies and corrections. Considerable economic saving can be obtained by solving this problem by methods other than to design completely stable system. Thus in order to utilize the system to its maximum capacity and economy it is essential to analyze the system completely. Also the high-speed relay techniques used as a best alternative to improve the transient performance of the system requires the precise determination of the critical clearing angle and time for stable operation. The methods available for the determination of critical clearing angle and time and the stability of the system under the faulted conditions are;

(1) The equal-area criterion

(2) Phase-plane analysis.

The Equal-Area Criterion :-

This is a simple graphical method to determine the conditions of stability for the system. It requires the plotting and inspection of swing curves. If these curves show the tendency of angle between two machine to increasing without limit, the system is unstable. Under the assumption of constant input, no damping, and constant voltage behind transient reactance, this method can be applied to any two machine system, whether they actually have only two machines or they are the simplified representation of a system with more than two machines. The two machine system can be divided into two types;

(1) One finite machine swinging with respect to an infinite bus

(2) Two finite machines swinging with respect to each other

One Machine Swinging with respect to an Infinite Bus :-

The swing equation of the finite machine is given by eq. (7) which on subsequent integration yields

$$\frac{d\delta}{dt} = w' = \sqrt{\frac{2}{M}\int_{\delta_o}^{\delta_m} Pa \, d\delta} \qquad (9)$$

where, δ_o = initial angle of the finite machine

Under steady state conditions after a disturbance, $w' = 0$ which requires

$$\int_{\delta_o}^{\delta_m} P_a \, d\delta = 0 \qquad (10)$$

which leads to the relation

$$\int_{\delta_o}^{\delta_m} P_i \, d\delta = \int_{\delta_o}^{\delta_m} P_u \, d\delta \qquad (11)$$

A plot of the curves of P_i and P_u vs δ are shown in Fig. 1. The relation (11) requires that the area $A_1 = A_2$ for stability. The use of this criterion wholly or partially eliminates the needs of computing swing curves and thus saves a considerable amount of work. The criterion can be applied to the sustained line fault and to the line fault with subsequent clearing.

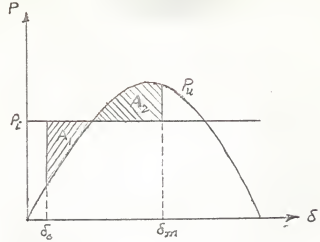


Fig. 1 The Equal-Area Criterion For Stability

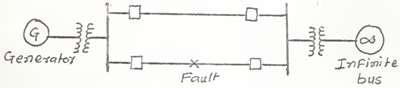
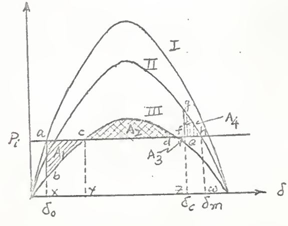


Fig. 2 Power System for One Machine Swinging with Respect to Infinite Bus



Curve I P_u under normal Condition

Curve II P_u Post fault condition

Curve III P_u during fault

Fig. 3 Determination of Critical Clearing Angle by Equal-Area Criterion

Two Finite Machines Swinging with Respects to Each Other :-

This involves practically the same analysis as one machine swinging with respect to the infinite bus, with the use of equivalent quantities for the swing equation. The equivalent quantities that are used has been shown to be,

$$M = \frac{M_1 M_2}{M_1 + M_2} \quad ; \quad P_i = \frac{M_2 P_{i1} - M_1 P_{i2}}{M_1 + M_2} \quad ; \quad P_u = \frac{M_2 P_{u1} - M_1 P_{u2}}{M_1 + M_2}$$

where M, P_i, P_u with appropriate subscript refer to machine 1 or 2 with their usual meaning.

Determination of Critical Clearing Angle by Equal-Area Criterion :-

The critical clearing angle plays vital role in the design of a stable system and its protective system. Critical clearing angle and time can be determined graphically by equating the area under the input line to the area above the input line for the complete range of the power angle curve. Consider the system, with the fault as shown in Fig. 2 on page 7.

The system will have input and output curves under all conditions as given by Fig. 3. By moving line zefg in Fig. 3, to the left or right make areas $A_1 + A_3 = A_2 + A_4$ or in other words make $\sum A = 0$. For this condition the value of δ_c gives the critical clearing angle. Any angle less than δ_c for clearing will assure stability, while clearing at angles greater than δ_c will lead the system to instability.

Phase-Plane Analysis :-

This method provides an easy way of examination of the nature of the solution of the swing equation. It can be predicted from the phase-plane that the system will become unstable about and beyond the saddle point and the syste will be stable about the vortex point. By correlating maximum and minimum potential energy with the nature of the singular points, a good amount of simplification is made

possible in determining the critical clearing angle. Complete development of this method is given in reference 16with help of a specific problem.

Neither the point-by-point method nor the equal-area criterion, nor the pre-calculated swing curves by themselves give the critical angle and critical clearing time simultaneously. Phase-plane analysis is the only method which can give both simultaneously, or otherwise, both methods involve equal amount of work.

HIGH-SPEED FAULT CLEARING AND RECLOSING CIRCUIT BREAKERS

General :-

The conditions of stability of the system greatly depends upon the amount of power transmitted, type of faults, location of faults, rapidity of clearing, and the method of clearing rather than depending solely on the system itself. Most of the faults on the overhead transmission lines are of transitory nature and they disappear, without causing any damage to the line, if the line is de-energized for a time sufficient for the arc to be extinguished. After the arc has become sufficiently deionized, the line may be re-energized and put back into service. Thus for most of the faults of transitory nature it is necessary to clear them quickly and to put the line back into service rapidly for reliable and continuous service. It has been recognized by experience and analysis that high-speed clearing of faults affords marked improvements in continuity of the service and the transient stability. Frequently a system which is unstable for a particular type of fault and fault location can be made stable by altering the existing relaying or by modernizing the circuit breakers so as to decrease the clearing time.

High-speed reclosure for improving stability is one step ahead of high-speed clearing of faults. Its effects on raising stability limits is especially marked when applied to single circuit ties between systems, for without reclosure the power limit of a single circuit tie is zero, whereas, with reclosure the power limit may be considerable. Also rapid reclosure on the long line or high-voltage line with an induction motor load shows the tendency of preventing fall out of induction motor load due to operation of undervoltage devices, as the clearing time reduced to fraction of a second causes voltage dips for very short duration.

Even though a line is reclosed when the generators are out of step or when they have such a large angular displacement that the synchronism is temp-

orarily lost after reclosure, it is possible that synchronism may be soon regained. This possibility is an additional reason for using rapid reclosure.

Factors Affecting the Feasibility of High-Speed Reclosure :-

The factors affecting the possibility of rapid reclosure of circuit breakers for maintaining stability and improving system performance are as follows;

1. The maximum time available for complete cycle of a operation of a circuit breaker tripping and reclosing without loss of synchronism. The factors determining the maximum available time for a complete cycle of operation can be enumerated as: (a) System arrangement and design; (b) amount and distribution of generating capacity; (c) load being carried on faulted circuit and remainder of system; (d) type, duration, and location of fault; (e) short circuit ratios and reactances of various generators; and (f) method of grounding. It is clear from the stability analysis studies that this maximum time for de-energization of the line without loss of synchronism is the same as the critical clearing time determined by one of the methods given in the previous section.

2. The least possible time in which the breaker can be tripped and reclosed, as determined by mechanical and electrical limitations of the breakers themselves, is independent of the system operation or fault condition. This is a matter of the design of the circuit breakers and their operating mechanisms. This also depends upon the voltage ratings and interrupting capacity.

3. The time required for the arc space to deionize so that the arc will not restrike when the breaker is reclosed. This again depends upon: (a) fault current and its duration; (b) length of arc; (c) number of conductors involved; (d) tower and circuit configuration; (e) insulator dielectric strength; (f) altitude; (g) length of line; (h) system voltage; (i) weather conditions. This time has been found from tests conducted in high voltage laboratories

and from field experience with reclosing breakers. Experiments showed that; (1) the probability of restriking increases with operating voltage for spacing ordinarily used; (2) the restriking of an arc is a random phenomenon; (3) the probanility of restriking is only slightly affected by a variation in currents; (4) restriking times are longer with a high-current arcs.

4. The probability of succesive lightning strokes within the reclosing period.

5. The probability of occurence of permanent faults.

6. The freedom of the line from mechanical troubles.

Effects of Fault Clearing Time on Transient Stability Limit :-

The effects of rapid fault clearing and rapid reclosing can best be visualized by use of the equal-area criterion. The time of fault clearing is the sum of the time that the protective relays take to close the circuit breaker trip circuit and the time required by the circuit breaker to interrupt the fault current. The power limit can be determined as a function of a clearing angle by the equal-area criterion, and the relation between clearing angle and clearing time can be found from the precalculated swing curves. The curve of stability as a function of clearing time has been derived.[13] The curve in Fig. 4 shows that the stability limit can be greately increased as the time of fault clearing decreased. On the other hand slow clearing may even sometimes cause permanent damage to the equipment as a consequence or may drive the system to instability.

Rapid reclosing followed by rapid clearing grants further increas in transient stability limit. For analysis of the system stability, under rapid reclosure conditions, by the equal-area criterion, power angle curves must be drawn for the several pertinent conditions: (1) before occurance of the fault; (2) during the existence of the fault; (3) with the fault cleared; and (4) with

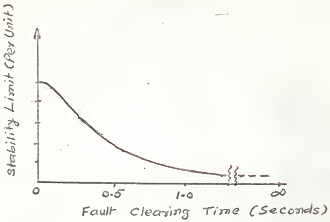


Fig. 4 Stability Limit As A Function of Fault Duration

Fig. 5 a

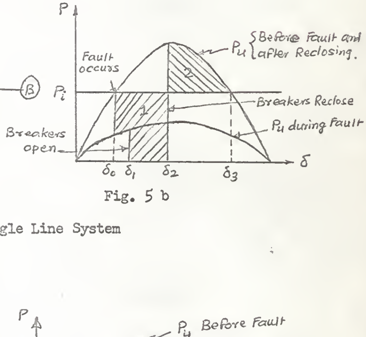


Fig. 5 b

Stability in Reclosing of Single Line System

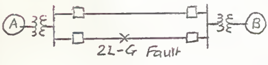


Fig. 6 a

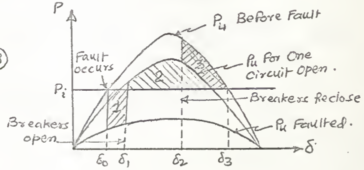


Fig. 6 b

Stability in Reclosing of Double Circuit System

the line reclosed which is, however, the same as the unfaulted curve.

First consider a simple two machine system of Fig. 5a, having a single circuit transmission line connecting two groups of generators A and B. The input power is assumed to be constant throughout the disturbance. Referring to Fig. 5b, for stability area 1 must equal area 2. The curves from δ_1 to δ_2 represent the time for which the breakers are open and so the circuit is open and the power limit is zero. Thus for single transmission line the power limit is zero unless it is reclosed. The maximum angle of swing without loss of synchronism is δ_3. Investigation of the nature of areas 1 and 2 indicates that for two breakers with equal reclosing time without arc re-establishment, the one with slower fault clearing time will be more favorable from the stability point of view.

Now consider the two machine system with double circuit transmission line subjected to a fault on one line. The system and power angle curves are shown in Fig. 6a and 6b respectively, for equal area criterion. For stability area 1 $<$ area 2 + area 3.

Though Fig. 5 and 6 give a fairly good understanding of the effects of reclosure upon stability, they are of little help in the numerical calculation of the stability limit because the switching angles δ_1 and δ_2 are unknown. Usually the switching times; i.e.; the clearing time and the reclosing times are known or assumed, for they depend upon the speed of relays and circuit breakers. Corresponding to these times, switching angles δ_1 and δ_2 should be found for assumed power and then the equal area criterion can be applied.

The analysis of the reclosure for single and double circuit transmission lines shows its unique applicability and advantages of rapid reclosure in single circuit systems. From the economy and design standpoint, single circuit transmission was the most desired one over multi-circuit system but the only drawbacks limiting its application were that of poor inherent stability, zero power limit during fault, and the frequent outage and discontinuity of service. Without

reclosure within reasonable time, the transient power limit is zero and the synchronism will be lost however fast the fault may be cleared. Automatic high-speed reclosing of the circuit breakers on single circuit lines following trip outs, makes the serviceability more nearly comparable with double circuit lines. Such a scheme contemplates a complete cycle of breaker tripping and reclosing within a time short enough to retain synchronism of generating source and permit the arc to extinguish. The gain in power limit in single circuit systems by reclosure is considerably higher. The gain in transient stability limit obtained by rapid reclosure in the case of a double circuit is not as high as it is in a single circuit or as obtained by rapid and ultrarapid clearing but it is a fair practice to employ rapid reclosure on a double circuit also to assure the improved serviceability.

High-Speed Single-Pole Reclosing :-

The advantages of fast reclosing of transmission line circuit breakers have been realized for a number of years from the experiences gained on the basis of three pole reclosure. Under the three pole reclosure of the circiut breaker operation, all three phases of the system are disconnected together, regardless of fault. This gang-operation of circiut breakers results in momentary complete shut off of power transmission tending to bring down the stability limit. Gang operation presents particular trouble in case of single circuit transmission systems where any operation of the circuit breakers brings complete discontinuity in the service for the duration in which the breakers are open. Considerable gain in the transient stability could be achieved if the breakers can be so arranged to trip only the faulty phase and thus allowing some power to flow through the remaining sound phases. So one step beyond three pole tripping and reclosing is single pole tripping. Single pole switching circuit breakers are

arranged so that on single phase-to-ground faults only the faulty phase wire is disconnected at each end of line and then immediately reclosed. This allows synchronizing current to flow over the other two sound phase conductors during the time the faulted phase wire is out of service.

Single pole switching has particular application in grounded neutral system for line-to-ground faults, but occassionaly it can be designed also for line-to-line faults and two-line-to-ground faults. Even though only the faulty phases are tripped the first time, all three poles should be opened and locked out after an unsuccessful reclosure in order to avoid sustained inductive interference with telephone circuits, which would be caused by zero sequence currents.

With single pole tripping, slower speed reclosing as compared to three pole operation can be utilized with a definite gain in the stability limit. On the other hand, the stability limit of a single-tie-line can be raised above the limit obtainable with three pole tripping and reclosing at the same speed. The increase in stability is greater in line-to-ground faults or line-to-line faults, considerable for two-line-to-ground faults, and nothing for three phase faults. The actual gain in transient stability limit realized with single pole operation can be visualized by referring to Fig. 7. The figure shows the gain by increasing speed as well as by single pole tripping.

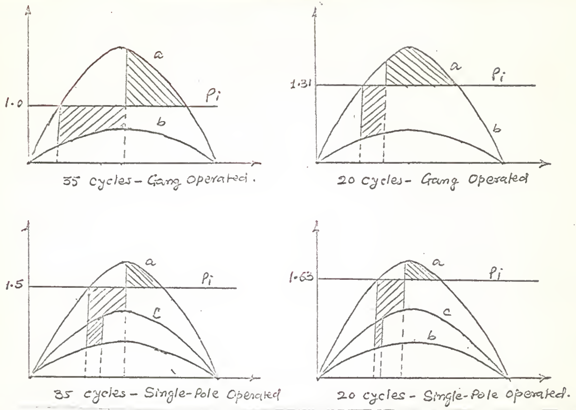


Fig. 7 Stability analysis with high-speed and single pole tripping

Curve a Sending end power angle curve before fault

Curve b Sending end power angle curve during single-line-to-ground fault

Curve c Sending end power angle curve with one phase switched out of service

It is indicated in the Fig. 7, that the single pole switching followed by high speed reclosure has considerable gain in stability limit. Also single pole switching decreases the amplitude of the swing and the consequent voltage dip during the swing. It also reduces the great mechanical shock to the generator at its coupling at the instant of reclosing. These additional advantages reinforce the preferable application of single pole switching in some systems where even three pole switching suffices to maintain system stability.

Disadvantages of single pole tripping are : 1. each breaker pole must be provided with its own operating mechanism so the switchgear is more expensive than for three pole tripping; 2. it requires relay scheme that will correctly select the faulted phase or phases under all conditions; 3. the effects of single

pole switching on the relaying of other lines and on inductive interference with telephone line are more remarkable and thus needs more detailed analysis.

Deionazation Time of Arc :-

Knowledge of deionazation time of the arc is most important because the circuit can not be reenergized until the ionization produced by the stroke has been dissipated enough and the insulating strength of the arc-space is restored so that it can withstand the restored voltage. It is the arc current and breakd own of insulation due to ionization of the air after the fault, which prevents the successful reclosure of the breakers. If the attempt is made to reclose the breakers before the arc has been completely deionized, there is a possibility of arc restriking resulting in tripping of a circuit breaker. As the deionization time of the arc is independent of the speed and design of circuit breakers, it is very important to know for how long a time a line must be deenergized in order to allow such complete deionization of the arc that will not restrike when the normal voltage is reapplied while utilizing high-speed reclosure as a tool for improving stability and service continuity. Information on deionazation time is available from two series of laboratory tests by Griscom and Torok in 1933[10], and by Sporn and Price in 1937[17]. The experiments showed that: (1) the restriking of arcs is a random phenomenon; (2) the possibility of restriking increases with operating voltage for spacing ordinarily used; (3) the probability of restriking is only slightly affected by large variations of currents; (4) restriking times are longer with high current arcs; (5) deionization time depends on gap length, fault current, fault duration, wind speed, and precipitation.

If single pole switching is used, the faulted conductor should be disconnected somewhat longer than is necessary when three pole switching is used, in order to obtain equal probability of successful reclosure. In other words, the permissible deionization time to maintain synchronism is appreciably longer if single pole switching is used as compared to three pole reclosure.

The results of experiments for high voltage with deionization time are as follows :

Line-to-line voltage r.m.s. kv.	Deionization time cycles on 60 c.p.s. basis
23	4
46	5
69	6
115	8.5
138	10
161	13
230	18

. Rapid Closing of Bus-Tie Switches :—

Rapid reclosure of circuit breakers has bean recognized as one of the most effective ways of improving transient stability. It is also possible to improve stability further by the rapid closing of a normally open switch such as bus-tie switch on a double circuit line. The possibility has been illustrated[9] by the results of calculations made on the particular power system shown in Fig. 8 a. The results of the effects of high voltage bussing at both ends of the line on the stability of the system when a two-line-to-ground fault occurs near the sending end of one circuit and is cleared by simultaneous opening of the breakers at both ends of the circuit is shown in Fig. 8 b. Curve B shows that the high voltage is detrimental during the fault. It is known that high voltage bussing is detrimental to stability as long as the fault is on the line but after clearing the bussing is beneficial because it lowers the reactance between generators by connecting two banks of transformers in parallel at each end of the remaining transmission line. This provides the clue towards the possibility of closing the bus-tie switch simultaneously with the opening of the breakers. The same protective relays

which open each line breaker could be use to close the nearby bus-tie switch.

When such switching is used, the calculated stability limit as a function of fault duration is shown by curve C of Fig. 8. The power limit is greatly raised through closing the bus-tie switches simultaneously with the opening of the line breakers. The increase in stability limit over that obtainable with the higher of curve A and curve B is greater at the intersection of these two curves, which is in the neighborhood of the clearing time afforded by the modern high-speed relays and breakers. The improvement attainable through rapid closing of bus-tie switches in conjuction with 8-cycle breaker is just equal in this case to the improvement attainable through replacing 8-cycle breakers with 5-cycle breakers.

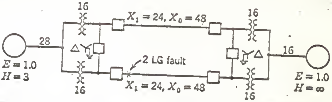


Fig.8 a, Power system used to illustrate the effect of high-voltage bussing on stability

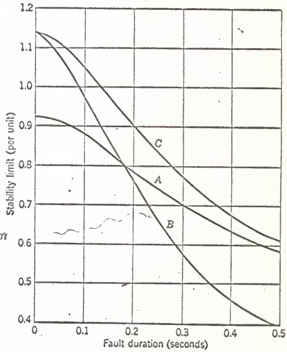


Fig. 8 b, Effect of the rapid closing of bus-tie switches on the stability

Curve A System without high-voltage bussing

Curve B System with high-voltage bussing

Curve C High-voltage system with rapid closing of bus-tie switches

Calculations in this particular system shows that the increase of stability limit due to rapid closing of bus-tie switches is three or four times as great as the increase obtainable through rapid reclosing of the line breakers if the clearing time is 0.15 second and the dead time is 0.25 second.

Rapid reclosing of the bus-tie switches has a further advantage in that it is effective even with permanent faults, whereas rapid reclosing is beneficial only with transitory faults and is detrimental with permanent faults. For this reason rapid reclosing of bus-tie switches could be applied to underground cable lines.

High-Speed Protective Devices :-

As was pointed out in previous sections, high-speed clearing of faults is recognized as the most economical and reliable means of improving stability limits. Developments and improvements in the operating mechanism, methods of arc extinction, and the available high-speed relays have made it possible for rapidy operating protective units to meet the requirements of the system stability limits. In recent protective devices, circuit breakers with total clearing times as low as 3 to 5 cycles, capable also of quick reclosure have become standard. These standard circuit breakers in conjuction with the fast operating one cycle carrier current relaying or HZ impedance type relaying, make the complete operation of clearing and reclosure possible in time less than 20 cycle which is sufficiently short duration to prevent any synchronous load from falling out of step. Recently circuit breakers with 3 cycle clearing times are becoming more popular and any further reduction in clearing time can not be expected to be of any additional benefit from a stability standpoint.

Circuit Breakers For Rapid Reclosure :-

High-speed reclosure circuit breakers are required to meet two conditions in addition to those rquired in ordinary clearing circuit breakers. They are : (1) in order to handle occasional permanent faults, the breaker must be capable of interrupting fault current twice or more rapidly in succession instead of twice 15 seconds apart as in standard duty cycle; and (2) the breaker must be provided with a suitable operating mechanism and also must be provided with the

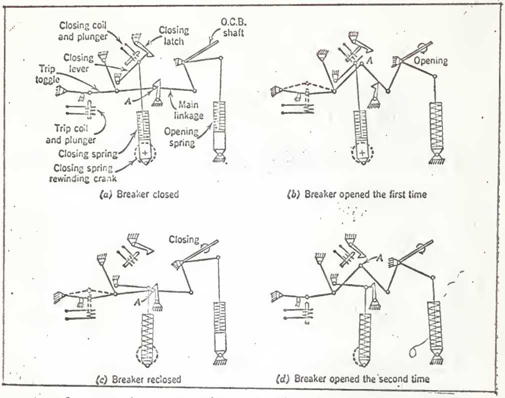


Fig 9, A spring-actuated mechanism for rapid reclosing of circuit breaker.

control circuit which, after tripping, will automatically reclose the breaker at high-speed and which, if necessary, will trip it a second time.

In order to meet the requirement of repeated interruption of the fault current, an oil circuit breaker must be equipped with modern arc-rupturing devices, such as ' De-ion' grids or oil-blast assemblies. When such devices are employed the contamination of the oil is minimized, leaving the path in condition for another arc interruption. Air-blast circuit breakers are best suited for reclosing service, because fresh air, blown through the arc space, rapidly restores the space to its original condition. This provision for arc-rupturing devices reduces the interrupting capacity of the circuit breakers.

In order to meet the requirement of suitable operating mechanisms, special mechanisms are used which give higher speeds than those attainable with standard reclosing solenoids. One type of spring actuated mechanism is shown

schematically in Fig. 9. It has two springs, one for opening the breaker and one for reclosing. These springs permit the operation of first opening, reclosing, and second opening without the necessary recharging of the springs. The breaker is held closed against the force of the open spring by a trip toggle and by the latch at A. Upon the occurance of a fault, the trip coil plunger trip the toggle, allowing pin A of the main linkage to move to the left and to escape from the latch. The opening spring opens the breaker by turning the breaker shaft clockwise, and brings pin A into the vicinity of the closing lever, as shown in Fig. 9 b. In the mean time the trip toggle has reset, Reclosing is initiated by energizing the closing coil, whose plunger release the closing latch. The closing spring then closes the breaker by counterclockwise rotation of the breaker shaft, as shown in Fig.9 c. The other latch then re-engages pin A. The closing spring is powerful enough to recharge the opening spring in readiness for a second opening.

Typical Pneumatic breaker Operating Mechanism :-

This is suitable for the reclosing service required. The construction is shown in Fig.10. The breaker is opened by spring and closed by the action of an air cylinder and piston. When it is desired to close the breaker, the magnetic pilot valve is energized, and this in turn opens the main intake valve or admits air through a throttle valve to the cylinder. The throttle valve regulates the flow of air to the cylinder in order to provide fast reclosing of the breaker. Near the end of the closing stroke, full air pressure is applied in order to positively close the breaker against possible short circuit forces and the full force of the opening springs. At the end of the stroke, the latch is closed and an auxiliary switch de-energizes and the magnetic pilot valve, shutting off air to the cylinder. For autamatic reclosing service, special control circuits are employed. After the breaker has been tripped by the protective relays, the trip coil is de-energized and the closing magnet is energized well before the end

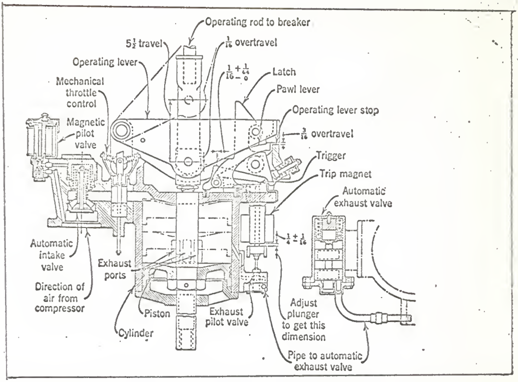


Fig. 10. Typical pneumatic operating mechanism for oil circuit breakers

of the opening stroke, thus reversing the motion of the piston and the breaker contacts.

Single pole tripping requires operating mechanism for each pole of the circuit breaker. Slower mechanisms can be used sometimes than that with three pole switching.

The reclosing time of a circuit breaker is the time from the instant when the trip coil is energized to the instant when the arcing contacts touch on the reclosing stroke. A reclosing time of 20 cycle is now common for high-speed reclosing service with 5 cycle breakers. Shorter times are readily obtainable on the pneumatically operated air-blast circuit brakers, the limiting speed of such breakers being determined by the time required for deionization of the line flashover.

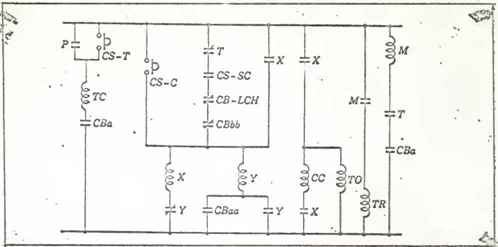


Fig. 11. Control circuits of an electrically operated circuit breaker with reclosing relay for providing a single immediate reclosure.

CBa Auxiliary switch on circuit breaker, closed when breaker is closed

CBaa Auxiliary switch which closes when circuit breaker mechanism is in operating position

CBbb Auxiliary switch which opens when circuit breaker mechanism is in operated position

CB-LCH Circuit breaker latch-checking contact, which closes when latch is reset

CC closing coil of circuit breaker mechanism.

CS-C Control-switch closing contact.

CS-SC Control-switch slip contact, which closes when handle is turned to 'close' and remains closed until handle is turned to 'trip'.

CS-T Control-switch tripping contact.

M Timing motor and contacts X Closing contactor.

P Protective-relay contacts, which closes when a fault occurs.

T Toggle-element contacts, which close when TO is energized and remain closed until TR is energized.

TC Trip coil of circuit breaker. Y Releasing contactor.

TO Toggle-element operating coil TR Toggle-element reset coil.

Control Circuits :-

The control circuits of a circuit breaker to which automatic immediate single-shot reclosing is applied should include the following features: (1) If the breaker is tripped by the protective relays after having remained closed for a while, it should be reclosed immediately and automatically. (2) if the breaker is tripped through the control switch, it should not be reclosed automatically. (3)if the breaker is tripped by the protective relays immediately after either closing by means of the control switch or automatic reclosing, it should not be reclosed again automatically, because a permanent fault is indicated. (4) in mechanical trip-free breaker operating mechanisms, the toggle or latch of the closing mechanism must be allowed to reset itself before the closing ciol is energized. Fig. 11 illustrates a typical control circuit which incorporates these features.

If the breaker is tripped by the protective relays after it has remained closed for a while, closing contactor X is immediately energized through the new reclosing path, in parallel with the control-switch closing contacts CS-C, through contacts T,CS-SC, CB-LCH, and CBbb; and accordingly the breaker is reclosed. When the closing coil CCis energized through contacts X, the operating coil TO of the reclosing relay is also energized. This coil opens back contact T in the reclosing path, thereby preventing a second reclosure if the breaker should be retripped immediately.

Relays for High-Speed operation :-

Choice of relay equipment is determined by the desirability of high-speed operation combined with nearly simultaneous energization of the trip circuits of the breakers at each terminal. In addition to initiating the simultaneous operation of the breakers at each end, the purpose of the protective relays

and relaying system is to operate the correct circuit breakers so as to disconnect only the faulty section from the system as quickly as possible, thus minimizing the trouble and damage caused by faults when they do occure.

These functions of the tripping breakers for all fault locations can be accomplished on some lines by the use of high-speed distance relays set to reach beyond the far end of the line. Where the scheme of high-speed distance relays is not applicable, carrier current relaying is the only practical system which provides high-speed operation of one cycle or less for any fault at any location on the circuit being protected.

If the protective relay can trip the breaker either in the event of fault or during large swings and out-of-step operation, it is desirable that reclosure should follow tripping from a fault, but that the breakers remain open after tripping from swings or out-of-step. The two conditions can be distinguished by the difference in rate of change of impedance.

In connection with single pole tripping, it is necessary to use a method of relaying that will properly select the breaker pole or poles to be tripped, according to which phase is faulted and according to the exact method of switching that is desired. It is also necessary to arrange the relay circuits so that all poles are tripped and locked out after an unsuccessful reclosure on any type of fault. Any relay scheme should be supplemented by a "phase-selector relay" when single pole switching is used.

Carrier Current Relaying Scheme :-

On long lines carrier current relaying is less expensive and more reliable for the simultaneous high-speed operation of the circuit breakers at the ends of the faulted sections though it has more expensive and complicated terminal equipment. Contrary to the common practice in pilot wire relaying, a quantitative comparision of the currents at the two ends of the line is not made in carrier relaying. Instead, the simplest possible signal is transmitted; that is, the

carrier is either on or off. The carrier current relay system requires protective relays, a transmitter-receiver unit, a coupling condensor, and a line trap.

Relays are of high-speed type. The transmitter consists of a master oscillator and power amplifier. The oscillator is turned off either by connecting its screen grid to a negative potential or by removing the plate-to-cathode potential. The receiver has a detector and sometimes a relay tube. The output of the receiver goes to protective relays. Each receiver on a two terminal line is tuned to the same frequency as the transmitter on the other terminal. The transmitter-receiver unit is connected to the high-voltage transmission lines through a coupling capacitor, so that the carrier transmitter-receiver unit is effectively insulated from the transmission line and ground at 60 cycles, yet connected to the line and insulated from ground at the carrier frequency. The reactance of the carrier current is compensated by adjustable series inductance in the line tuner. The line-trap, consisting of the parallel combination of inductance and capacitance tuned to the carrier frequency, is connected in series with the line conductor at each end of the protected transmission lines. The purpose of the trap is to confine the carrier power to the protected section, thus assuring ample signal strength unaffected by switching operations or line-to-ground faults on other circuits. The carrier circuit may consist either of two of the three line wires or one of the wires with ground return. The ground return circuit has greater attenuation and greater interference than the metallic circuit but on the other hand, it requires only half as many coupling capacitors and wave traps. It is usuallu satisfactory for relaying purposes, but the metallic circuit is preferable for communication.

The carrier current relay developed and used for ultrarapid reclosure of circuit breakers on high volage transmission lines is shown in Fig. 12. The relay operates in one cycle or less time, energizing circuit breaker trip circuits

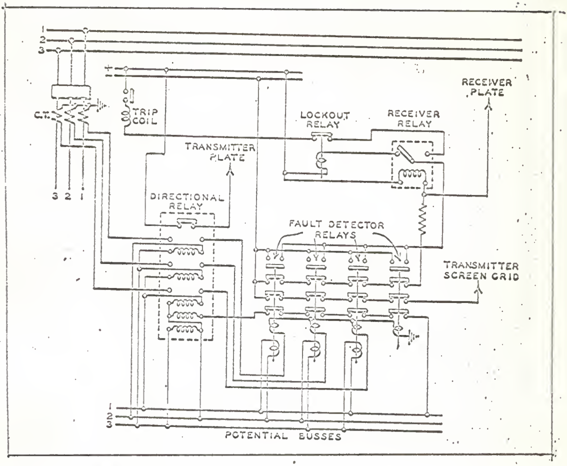


Fig. 12. High-speed carrier current relay.

at both ends of the line simultaneously. The trip circuit is normally held open by the receiver relay and it is closed only by the dropping out of these relays when no carrier signal is received. Since the relays controlling the trip circuit at both ends are simultaneously de-energized by the stoppage of the carrier signal, the actual closing of the trip circuit will occur at nearly the same time. Parts of the relay are;

1. Receiver Relay : This is a polarized relay having a field winding and an operating winding arranged to be energized either from the local battery circuit or from the carrier signal. The relay will close its tripping contacts when de-energized and hold the tripping contacts open normally when excited from the battery circuit and during fault conditions when excited from the received carrier singal. The relay will close its lockout contacts when energized and hold them closed normally when excited from the battery circuit and during

fault conditions when excited from the received carrier signal.

2. Fault Detecting Element : There are three for phase faults; these being of the impedance type, having a current operating winding and voltage restraining winding. All of these fault detectors are equipped with four independent contacts for performing the following functions :

   a. A circuit opening contact for starting carrier by removal of the grid bias;

   b. A circuit opening contact for disconnecting a receiver relay coil from the local battery supply;

   c. A circuit opening contact for removing the voltage restraint from a directional relay; and

   d. A circuit closing contact in series with the receiver relay and tripping circuit.

3. Directional Relay : This is the polyphase type, having voltage restraint. This relay is of the new induction-cup type, giving it greater speed than was obtainable with the previous type of power directional relay.

4. Lockout Relay : This is a time delay circuit opening and circuit closing auxiliary relay of the plunger type which is adjustable to give a time delay of 5 cycles in opening or closing.

Sequence of Operations :

Under normal conditions the directional relay contacts are held closed by voltage restraint, applying plate voltage to the transmitter but the transmitter does not operate because of the normally closed contacts of the fault detector relays which apply a negative bias to the screen grid of the transmitter. The receiver relay contacts are held open by the closed contacts of the fault detector relays energizing the receiver relay coil from the station battery. In case of internal fault the directional relays will operate to stop transmission of the carrier at both ends of the line. When

the carrier from both ends has been stopped and the receiver relays are de-energized and they both drop out completing the trip circuits. The receiver relay operates in an average time of 0.35 cycle. The directional relay opens its contacts in an average time of 0.4 cycle, so that the fundamental fastest time possible is 0.75 cycle. On an external fault the directional relay on the end where power is flowing from the line into the bus will permit the carrier signal to be maintained, thereby preventing tripping. The function of the lockout relay is to open the trip circuit 5 cycles after the circuit closing contacts of the fault detector have closed to prevent false tripping on a through fault as the result of sudden reversal of power flow and to prevent tripping in case of system instability.

Phase-Selector Relay for Single-Pole Switching :—

The chief problem involved in single pole tripping is to find an effective way of indicating which phase conductor is supplying the ground current. Alternative solutions to this are either to provide an undervoltage relay energized from line-to-ground voltage or to use voltage restraint overcurrent relays operating on line current and line-to-ground voltage. Adaquate sensitivity is not provided in either of these methods.

The ideal approach to the problem would be to find a method of phase selection which can be made just as the conventional direction ground relay and which is totaly independent of all normal conditions and dependent solely on the fault conditions. The method utilizing the phase shift of one sequence component with respect to another sequence component meets the above requirements.

Zero sequence components rotate around a given phase of the negative phase sequence system in 120° steps. Fig. 13 shows the current vectors for single-phase-to-ground faults on different phases. The selector elements utilizing zero and negative sequence currents will act in a one direction for phase A-to-ground fault but will act in the opposite direction for ground faults on phases B and C. Thus if a directional element with a watt-element

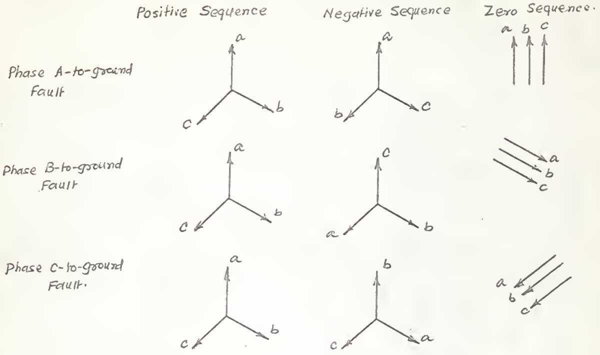


Fig. 13 Current vectors for single-phase-to-ground fault on three phases

characteristic is suppleied with the zero sequence current in one coil and the phase A component of negative sequence current in the other coil, then on a phase A-to-ground fault this element will have maximum torque in the contact closing direction. For a fault on phase B the zero sequence current leads phase A of negative sequence 120° and the element will therefore have torque in contact opening direction. An actual installation of phase-selactor relay co-ordinated with a distance type carrier scheme has been made and tested with very satisfactory results.

The connections of the phase-selector relay are shown in Fig. 14. Negative sequence currents are supplied to the selector relay from a negative sequence filter having three-phase output. The directional overcurrent ground relay may be polarized either by voltage or by current, This relay determines whether or not the fault is in the tripping direction. The action of the phase selector relay is independent of the direction to the fault, because a change of direction reverses all components of current with respect to the voltage without altering the phase difference between the zero sequence and

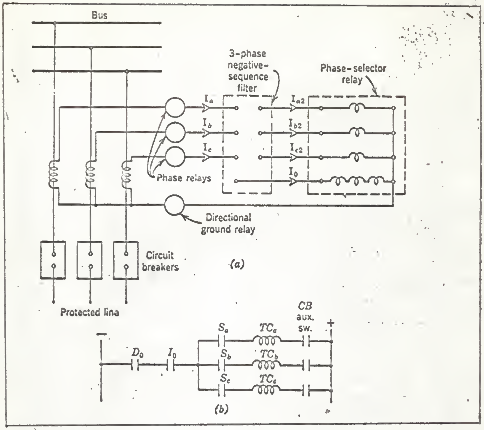


Fig. 14. Simplified diagram of connections of phase-selector relay

a. Current circuit b. Trip circuit

negative sequence currents. There is no tendency to trip the sound phase while one wire is open, but during a two-line-to-ground fault the selector relay selects the unfaulted phase so the phase relay must be given the control. The high-speed impedance relays are supplied with star current instead of the usual delta current. This gives a balance point the position of which varies according to the type of the fault, and the relay must be set to prevent over-reaching on external two-line-to-ground faults.

RELATIVE ADVANTAGES AND DISADVANTAGES OF ALL STABILIZING METHODS

The proposed methods of increasing reliability of systems through prevention of faults or through lessening the severity of their effects are:

(1) overhead ground wires;

(2) protector tubes;

(3) ground fault neutralizers;

(4) rapid reclosure;

(5) quick response excitation; and

(6) the series resistance method of increasing transient stability limit.

Out of all these, only rapid reclosure provides the most effective means for decreasing the probability of loss of synchronism and for increasing the reliability of electric power service.

Overhead ground wires serve to prevent most flashovers of line insulation by lightning strokes. Protector tubes serve to extinguish the power arcs which follow flashover of insulation by lightning. Grounding of the neutral points through ground neutralizers (petersen coils), which resonate with the zero sequence capacitance, prevent line-to-ground faults whichcomprise about 80% of all faults from being short circuits and make two-line-to-ground faults have merely the effects of line-toline short circuits. Ground faults neutralizers make transitory line-to-ground faults self-clearing and make possible the continued operation of a power system having a permanent line-to-ground fault until the fault can be located and repaired. They are applicable to cables as well as to open wires. All these three devices serve to reduce the number of circuit breaker operations but do not eliminate the need for the circuit breaker.

Quick response excitation increses stability under fault conditions by reducing demagnetization, but it is usually insufficient alone to maintain

stability for the most severe faults such as three-phase faults.

In the series resistance method, the resistance is inserted in series with generator during and after a short circuit to increase the transient stability. The series resistance loads the machine during fault and generally reduces the normal tedency to overspeed. After the fault has been cleared the series resistance exerts a powerful influence in retarding excessive overswing by taking advantage of the generator stored energy relative to that of the load center. The cost will generally be lower than the combination of other measure economically taken such as high inertia generators, low reactance of generators and transformers, damper windings, transformer neutral impedance, special simultaneous relay schemes or other remedial measures such as lightning proof lines. The use of series resistance increases the generator output at the sacrifice of the cycle of operation while the fault is on and after it is cleared.

The high-speeddreclosure breaker tends to reduce faults to mere switching operations, thus minimizing the importance of the method of neutral grounding, and cases resulting from switching effects must be overcome by other means. High-speed circuit breakers and relays offer great promise for improving power system performance at times of faults, constituting probably the most economical single measure for this purpose. They make it possible to withdraw three phase faults at the most severe locations without causing instability, a condition frequently impossible otherwise.

CONCLUSIONS

Transient stability of a power system depends largely upon the duration of the fault. The larger the cleating time the more are the possibilities of losing synchronism and causing permanent damage to system equipment. High speed clearing of the fault has proved to be the most effective and economical way of increasing the power system stability. High-speed reclosing for improving system stability proves the best method among all other stabilizing methods. High-speed reclosing will show the greatest advantage and will tend to be more generally used as the number of system interconnections and the size of the system increases, relative to the strength of their individual interconnecting ties. Ultrarapid reclosure has proved itself as a tool of major importance in planning and building any overhead high-voltage transmission system. Under favorable conditions for its use, rapid and ultrarapid reclosing provides a simple and prominent means for substantially increasing power limits and the system reliability. On high-voltage lines properly insulated and provided with ground wires 90% successful reclosure could be obtained by the use of ultrarapid reclosing as now developed. On double circuits and particularly on single circuits, the reclosure performance and the power limits can be improved greatly by decreasing the time of fault duration and thus speeding up the reclosure cycle. The recent development of 3-cycle breakers, making possible 12 cycle reclosure, makes the service more reliable. In case of severe faults, rapid closing of bus-tie switches proves much more useful than the rapid reclosure. High-speed clearing in addition to increasing stability, minimizes the possibilities of damage to insulators and conductors and minimizes the possibilities of developing less severe faults into more severe faults and ultimately complete outage of the line.

BIBLIOGRAPHY

1. Bergvall R.C.,"Series Resistance Method of Increasing Transient Stability Limit", A.I.E.E.Transactions,vol. 50, 1931, pp 490-4

2. Bhon R.P., and Le-Bosquet R.J.,"Maintaining Power System Stability Through High-speed Relaying", Electrical Engineering, August 1963, vol. 82, No. 8, pp 507-12

3. Crary S.B.,"Power System Stability", vol. II, John Wiley & Sons, Inc.,New York, 1947

4. Crary S.B., L.F. Kennedy, and Woodrow C.A.,"Analysis of the Application of the High-speed Reclosing Breakers to Transmission System",A.I.E.E.Transactions, vol. 61, 1942, pp 339-48

5. Cunningham R.C., and Hill A.W.,"A Compressed-air Opening Mechanism for Oil Circuit Breakers", A.I.E.E.Transactions, vol. 61, Sept.1942, pp 695-8 and Disc. pp 1019-20

6. Evans R.D., and W.A.Lewis,"Selecting Breaker Speeds for Stable Operation", Electric World, vol. 95, February 15, 1930, pp 336-40

7. Edgerton H.E.,and Lyon, W.V.,"Transient Torque-Angle Characteristicts of Synchronous Machines", A.I.E.E.Transactions, vol. 49, 1930, pp

8. Goldsborough S.L.,"High-Speed Relays Increase System Stability", Electric Journal, vol. 27, July 1930, pp 400-401

9. Goldsborough S.L., and Hill A.W.,"Relays and Breakers for High-Speed Single-Pole Tripping and Reclosing", A.I.E.E.Transactions, vol. 61, 1942, pp 77-81

10. Griscom S.B., and Torok J.J.,"Keeping the Line in Service by Rapid Reclosing", Electric Journal, vol. 30, May 1933, pp 81-93

11. Johnson J.T.Jr., and Graff J.W.,"Results with Quick Reclosure of 110 kv. Breakers," Electric World, vol. 105, Sept. 14, 1935, pp 2214-6

12. Kimbark E.W.,"Improving Stability by Rapid Closing of Bus-Tie Switches", A.I.E.E.Transactions, vol. 64, 1964, pp 61-4

13. Kimbark E.W.,"Power System Stability", vol. I, John Wiley & Sons, Inc., New York, 1948

14. Kimbark E.W.,"Power System Stability", vol. II, John Wiley & Sons, Inc., New York, 1950

15. Park R.H.,and Bancker E.H.,"System Stability as Design Problem", A.I.E.E. Transactions, vol. 48, 1929, pp 170-93

16. Rao N.Dharma,"A New Approach to the Transient Stability Problem", A.I.E.E.

Transactions, June 1962, No. 60, part III, pp 186-91

17. Sporn,Philip, and Prince D.C.,"Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines", A.I.E.E.Transactions, vol. 56, 1937, pp 2214-16

18. Spron,Philip, and Muller C.A.,"Experiences with Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines", A.I.E.E.Transactions, vol. 58, 1938, pp 625-31

19. Spron,Philip, and Muller C.A.,"Nine Years Experience with Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines", A.I.E.E.Transactions, vol. 64, 1945, pp 225-28

20. Sporn,Philip, and Muller C.A.,"One Cycle Carrier Relaying Accomplished", Electric World, vol. 105, Oct. 12, 1935, pp 26-8

21. Schwager A.C.,"Test of 230 kv. Reclosing High-Speed Oil Circuit Breakers," A.I.E.E.Transactions, vol. 63, November 1944, pp 784-8; Disc. pp 1468-71

22. Stoker J.J.,"Nonlinear Vibrations in Mechanical and Electrical Systems", Interscience Publishers, Inc., New York, 1950

23. Traver O.C., and Muller E.H.,"A Faster Carrier Pilot Relay System", A.I.E.E.Transactions, vol. 55, June 1936, pp 688-96

24. Treat R., and Verwoert H.C.,"Service Continuity Prompted by Rapid Breaker Reclosure", Electric World, vol. 100, August 1932, pp 172-5

25. Trainer,J.J., Hobson J.E., and Muller H.N.,"High-Speed Single-Pole Reclosing," A.I.E.E. Transactions, vol. 61, 1942, pp 81-7

26. Van C.Warrington A.R.,"Protective Relays", John Wiley & Sons, Inc., New York, 1947

THE STUDY OF EFFECTS OF POWER SYSTEM PROTECTIVE UNITS WITH SPECIAL REFERENCE TO POWER SYSTEM STABILITY

by

Devendra S. Rajparia

B.Tech., Indian Institute of Technology, Bombay; India.

1962

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirement for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1964

Approved by:

Major Professor

Transient stability of electric power systems is an ever existing problem which requires continuous study and correction. The factors such as increasing power requirements, developments of high voltage and high capacity transmission lines, necessities for location of power stations remote from the load centers and long distance transmission, increasing requirements of continuity of industrial loads and the involved complexities in distribution and their control system made the problem of transient stability more severe. Whether the system is stable during the fault will depend not only upon the system itself, but also on the type of faults, location of faults, rapidity of clearing, and the method of clearing, in addition to the amoünt of power that can be transfered from one section to another, without loss of synchronism when the system is subjected to a fault. The rapid opening of the circuit breakers on a faulted line proves one of the most effective ways of improving power system stability. Recent developments and improvements in the speed and performance of circuit breakers and relays have made the high-speed clearing of faults practicable. Also if loss of synchronism is not to occur, not only must the fault be cleared quickly but the line must be restored to service after the fault is removed before the two systems have drifted far enough apart to cause instability. Thus a rapid opening followed by a rapid closing has been used more recently and gives further improvement in stability if the fault is transitory. Present trend in the design of most economical and reliable systems is the employment of the rapid and ultrarapid reclosing circuit breakers for the system protection.

This report mainly deals with some of the basic aspects of the power system stability with little emphasis upon the solution of the power system swing equation by numerous approximate methods. Because of the complexity of the system and the difference in behavior of system components under different conditions, it is difficult to give suffucient consideration to every factor contributing to

the power system stability. Also due to the non-linear nature of the swing equation the exact solution of the actual system has becomemuch more difficult. A number of attempts have been made in past to approximate actual system by an equivalent hypothetical systems, and to obtain the approximate solution. Graphical methods such as the equal area criterion and the phase-plane diagram as well as analytical methods are presented. Special attention is directed to calculations of the critical fault clearing time of the system with maximum power transfer without loss of synchronism. Special emphasis is laid upon the analysis of the system with high-speed and ultrahigh-speed reclosure on the faulted system. The report also presents the results of past experiences with high-speed protective devices in power system. Some of the modern high-speed circuit breakers and relays are included with the construction and performance described in brief.